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14. ABSTRACT
We have studied the ignition of fuel sprays and solid rocket fuels by the photo-ignition of single wall carbon nanotube (SWCNT) with an ordinary camera flash. Our investigation includes the effects of O2 concentration and the presence of solid oxidizers such as ammonium perchlorate (AP) on the minimum ignition energy (MIE) as well as the duration and temperature of the reaction. We have shown that by mixing CNT with other nanoparticles and powdered material, the ignition parameters such as ignition delay, burn temperature, and burn duration can be adjusted. We believe this approach in photo-ignition of fuel spray and solid fuel provides a suitable method for ignition of liquid rocket engines and solid rocket motors. Among the advantages of this approach are a very low weight and a robust ignition method, and it enables volumetric distributed ignition of fuel sprays and solid fuels. The proposed method is scalable for applications in very small as well as large liquid rocket engines and solid rocket motors.

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Photo-ignition of Liquid Fuel Spray and Solid Rocket Fuel by Carbon Nanotube Utilizing a Camera Flash

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Overview

- Objectives
- Photo-ignition (PI) phenomenon
- Nano-structured carbon & carbon nanotubes
- Experimental approach
- Experimental setup
- Ignition of liquid fuel spray by PI of CNT
- Ignition of solid fuel by PI of CNT
- Planned work
- Summary & Conclusions
- Photo-ignition of CNT for space applications

Objectives

Utilize photo-ignition of carbon nanotube (CNTs) and other nano-structured materials as agents for ignition of liquid-fuel sprays and solid rocket fuels

Such an ignition system offers the following advantages:

-Light weight and low cost

-Safe and flexible for ignition of different types of rocket

-Scalable for the ignition of very small as well as large rockets

-Provides the distributed ignition capability

-A softer-starting ignition system which offers distributed ignition capability and potentially improve the combustion stability

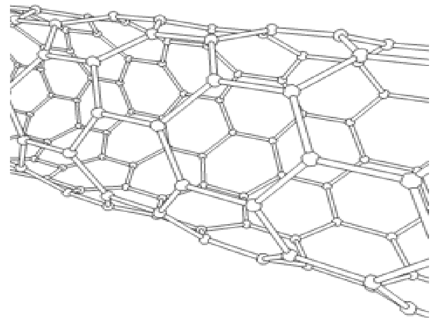
Photo-ignition Effect

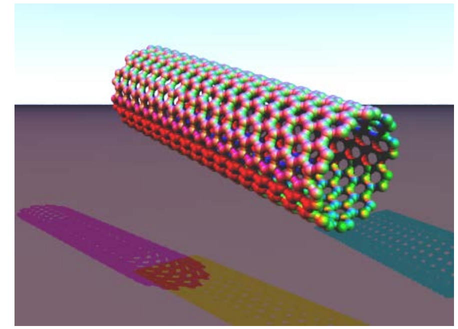
Photo-ignition (PI) Phenomenon:

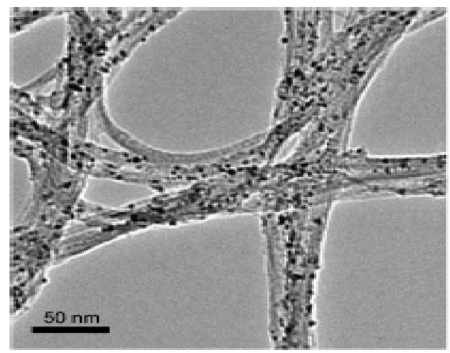
- PI is the ability to ignite a material by a flash of light
- While ignition of material with laser light has been around for a few decades, ignition of liquid and solid fuel by a compact camera flash is new
- PI of carbon nanotubes (CNTs) by a camera flash was first reported in 2001 by Smally et. Al. at Rice Univ.
- We used a camera flash with t< $1 J/cm^2$ per pulse for PI
- We studied PI of CNTs, graphene oxide (GO) foam, aluminum nanoparticles (Al-NP), and metallic powders
- We focused on PI of carbon nanotubes (CNTs) because it is the most promising candidate for ignition of rocket fuels

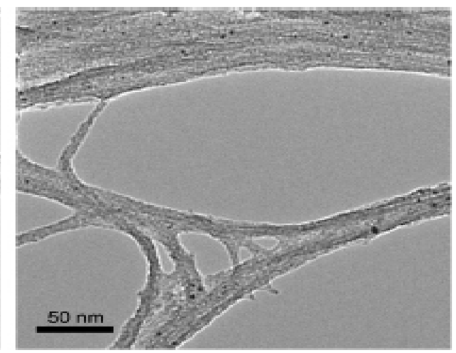
Overview of Properties of SWCNT

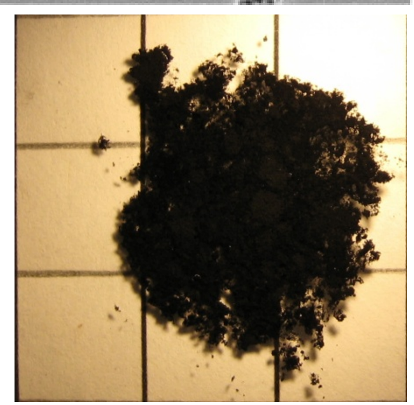
- Single Wall Carbon Nanotubes (SWCNTs) are carbon clusters, closely related to C-60 or bucky-balls and graphene sheets
- They are formed around nano-particles (acting as catalysts) most notably metal nano-particles, Fe in our samples
- Photo-ignition is only reported for SWCNTs and no other forms of carbon nanostructures or other nano-particles
- When exposed to a camera flash CNTs ignite with a glow and leave behind ash and Fe oxide
- CNT can be used as an ignition agent











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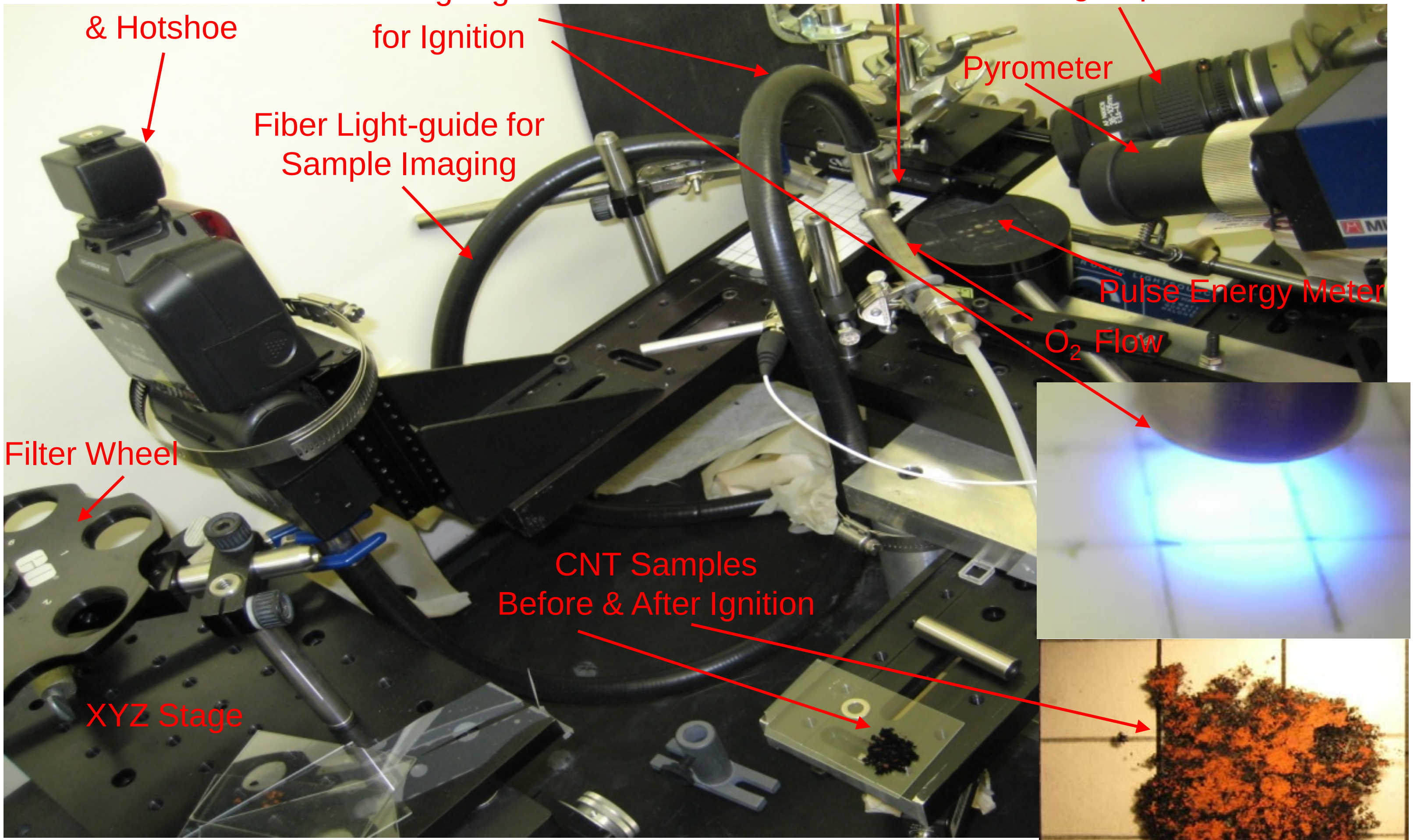
Experimental Approach

Achieving the Objectives though:

- Setting up a photo-ignition test bench for dry & wet CNTs
- Characterizing minimum ignition energy (MIE) for different nanoparticles
- Investigating the photo-ignition effect as a function of parameters such as; physical properties of the materail, pulse duration of light, and the nano-particle (Fe, Al) content of the sample
- Investigating effects of fuel injection design, fuel/oxidizer mixing concentration of nano-ignition agents (CNT and Al) and presence of gaseous or solid oxidizer on photo-ignition
- Use of encapsulated CNT + metal nanoparticles + simulated solid rocket fuel (SRF) for photo-ignition
- Design, assemble, and test of a combustion chamber for investigation of photo-ignition of liquid sprays and SRF at low and high pressure

Experimental Setup for Investigation of Photo-ignition in Nano-materials



Capabilities and components of the system

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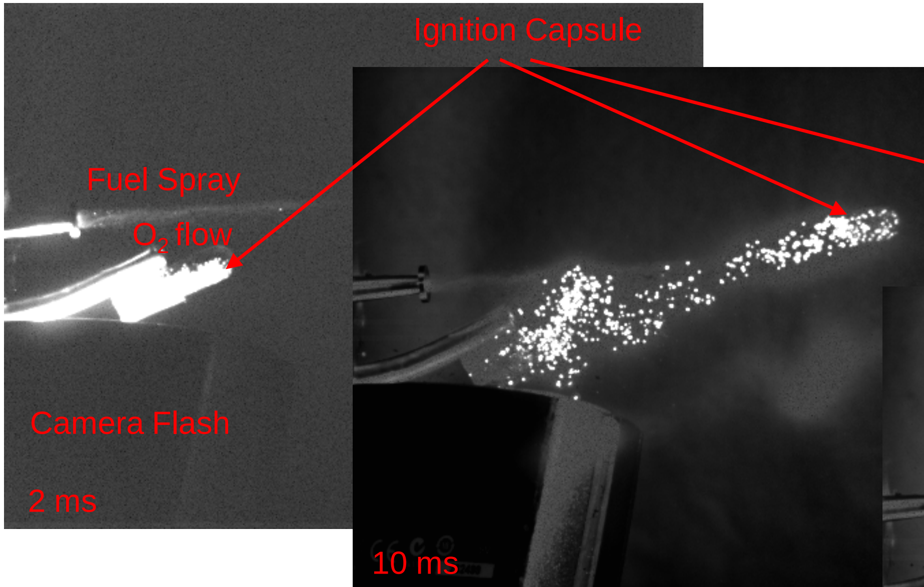
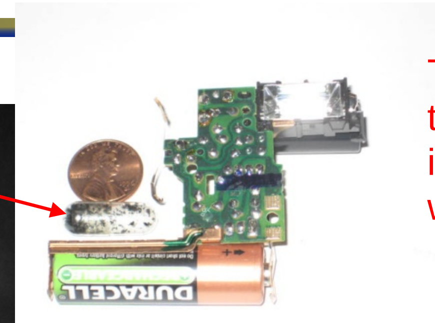
Photo-ignition of Different Nanoparticles

Nanoparticle Samples	Particle Size	Min. Ignition Energy (mJ/cm^2)	Ignition/Burn Temperature (^oC)
CNT(51% Fe)	< 30 nm	69 ± 7	500 ± 30
CNT(39% Fe)	< 30 nm	84 ± 10	470 ± 50
CNT(30% Fe)	< 30 nm	100 ± 10	450 ± 50
CNT(18% Fe)	< 30 nm	180 ± 50	420 ± 50
Graphene Oxide Foam	nm thick platelet	650 ± 100	450 ± 70
Al-nanoparticles (Al-NP)	18 nm	290 ± 50	> 1200
Fe-powder	> 200 nm	190 ± 30	220 ± 30

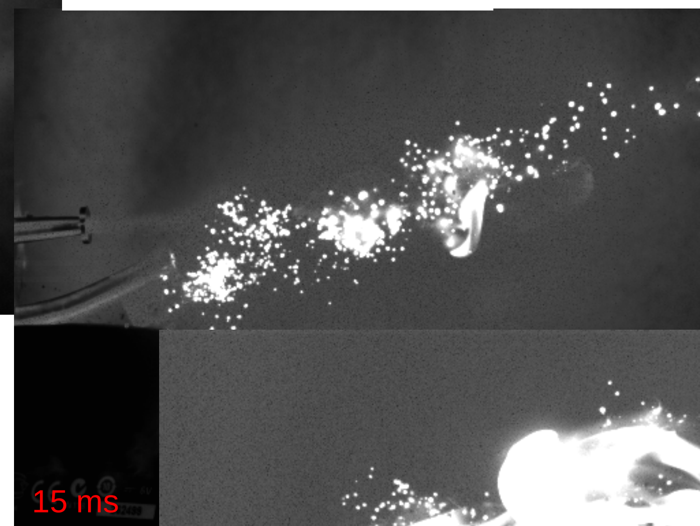
- CNT shows the lowest minimum ignition energy
- Aluminum NP shows the highest burn temperature

Ignition of Fuel Spray through Photo-ignition of CNT





The Xe-flash lamp and the electronics from an instant camera along with the Ignition Capsule



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Sequence of events after the encapsulate CNT was exposed to a camera flash (t= 0)

- **t=2 ms:** The ignition capsule containing CNT was held near a fuel spray when it was exposed to a camera flash (~1 J/cm^2 for a1ms pulse)
- **t=10 ms:** the cell bursts open and shoots ignited particles across the path of the spray
- **t=15 ms:** burning particles ignite the fuel and oxygen mixture in <u>multiple regions along their path</u>
- **t=20 ms:** flame spreads through the combustible mix

(images were captured at 2000 FPS)

Photo-ignition of CNT & Fuel Burning

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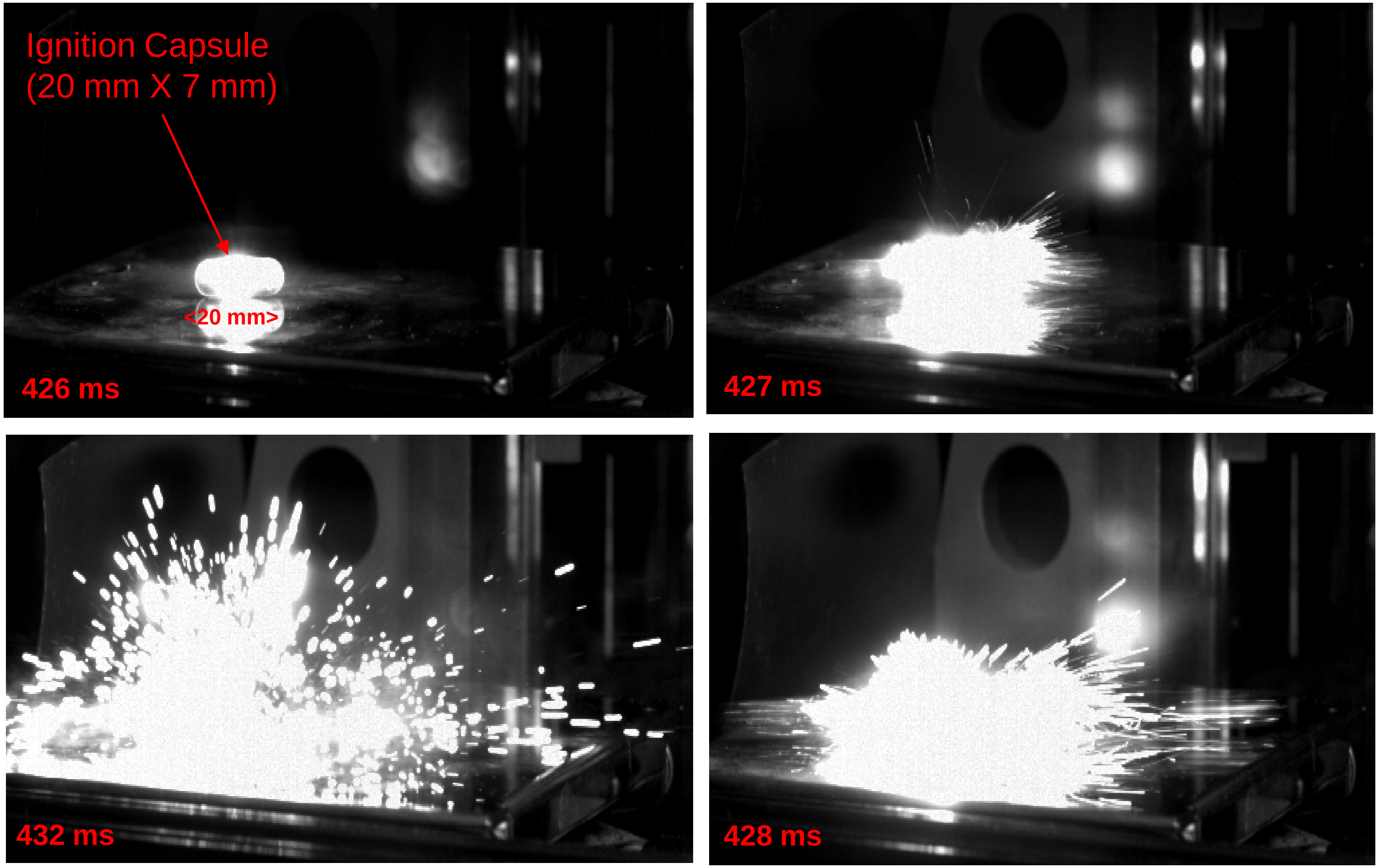
Photo-ignition of CNT + Al-NP + Simulated Solid Rocket Fuel (SRF)



Delayed (T=0 to 500 ms) photo-ignition sequence, clockwise: t= T+2, T+3, T+4 & T+8 ms after flash (images were captured at 2000 FPS, ~0.5 ms exposure)

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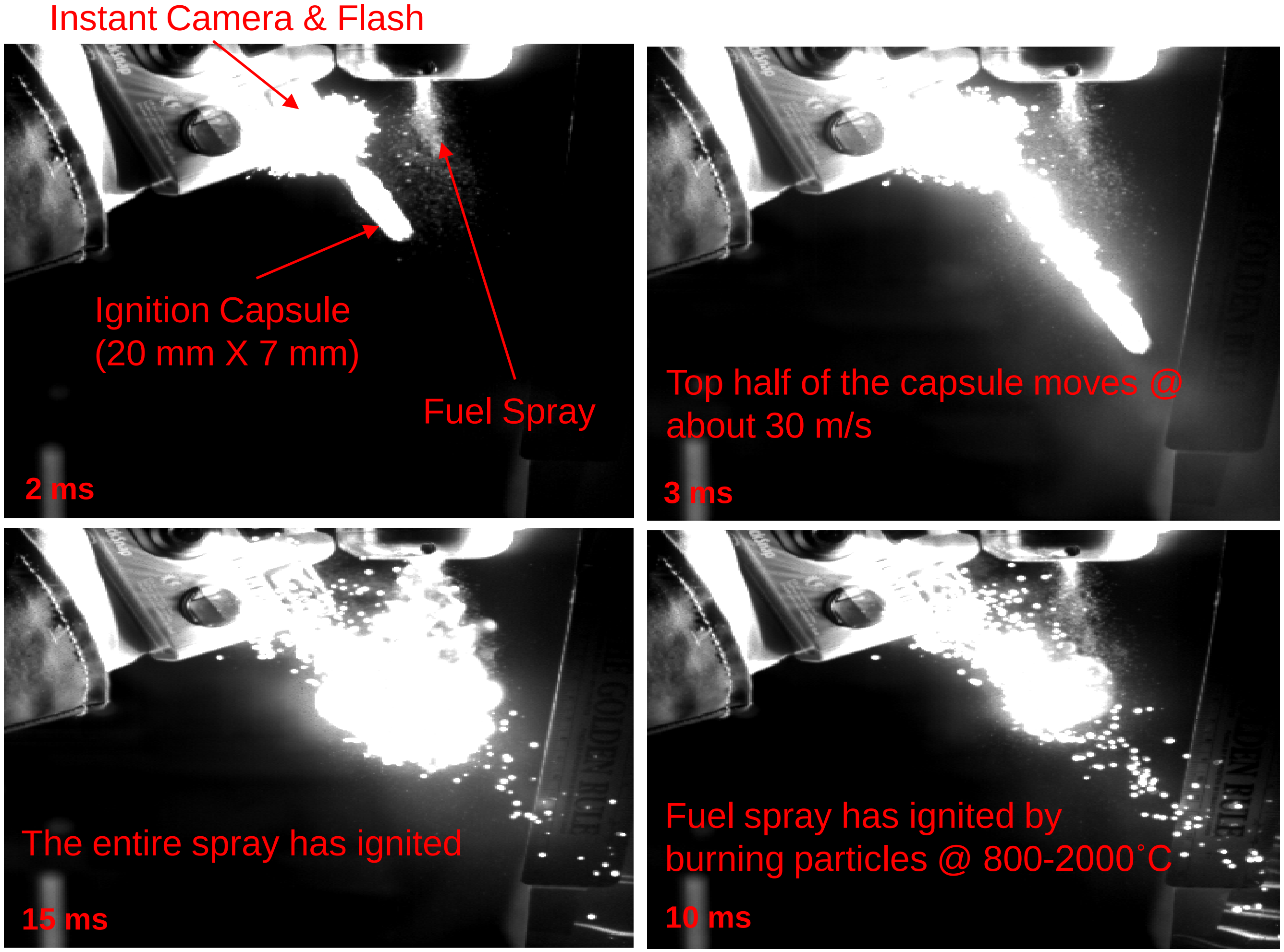
Photo-Ignition of CNT Leading to Ignition of Liquid Fuel Spray



Ignition of fuel spray via an encapsulated CNT by an instant camera flash; clockwise: t= 2, 3, 10 & 15 ms, where the entire spray is ignited

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Photo-ignition of CNT for Mixed Fuels

- Fuel burning with CNT

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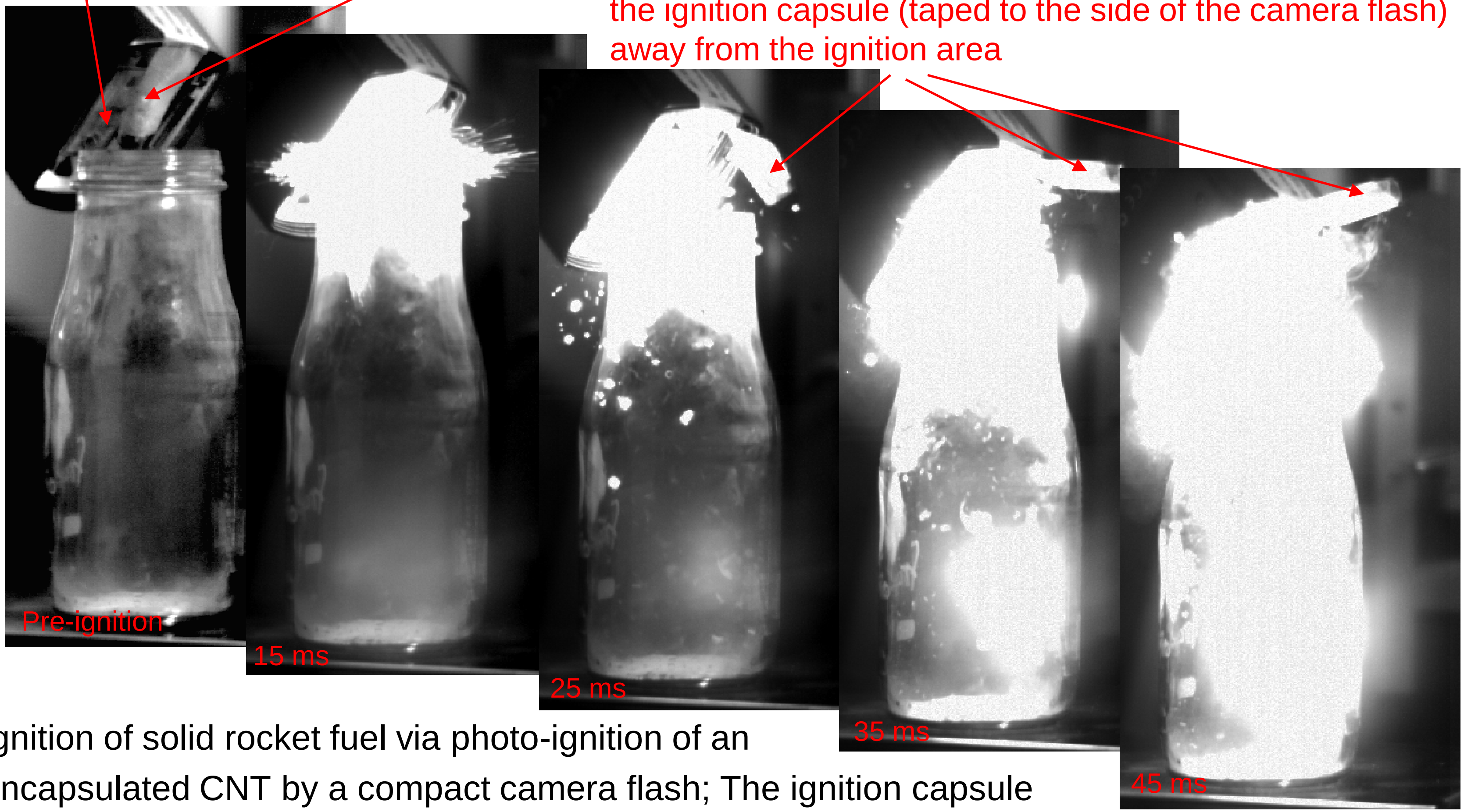
Photo-ignition of CNT + Al + SRF



Ignition of solid rocket fuel via photo-ignition of an encapsulated CNT by a compact camera flash; The ignition capsule contains CNT (~2 mg), Al powder (~20 mg) & SRF (~200 mg)

Images (from left): Pre-ignition, t=15, 25, 35 & 45 ms, where the container (D= 2.5” & L= 6.5”) is filled with burning debris at about 2000˚ C.

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Solid Fuel Burning by Photo-ignition of CNT

The glass container represents a volume similar to the hollow propellant cylinder within a typical test solid rocket motor

The ignition capsule is similar to a tiny rocket

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Planned Work

- Design and fabrication of a new combustion chamber to systematically study ignition of encapsulated CRT + Metal-NP + SRF
- Test and characterization of photo-ignition at low and high pressure & at low oxygen environment
- Photo-ignition of a test solid rocket motor (single stage/grain)
- Photo-ignition of a test liquid rocket engine at elevated pressure
- Qualification of the encapsulated CNT-based ignition system for small and large rockets
- Create PI of CNT with solid oxidizer in vacuum
- Design of ignition capsules as ultra-light rocket for maneuvering in space
- Design for repeated ignition cycles in liquid rocket engines

Summary & Conclusions

- Photo-ignition of a number of nano-structured material has been achieved by a compact camera flash
- CNT is the best candidate for ignition of different fuels by a compact camera flash < 1 J/cm^2
- Ignition of liquid fuels spray and simulated solid rocket fuels (SRF) was achieved with encapsulated CNTs utilizing a camera flash with a pulse energy of < 0.1 J/cm^2
- The ignition characteristics of encapsulated CNTs may be modified through addition of other nanoparticles, metallic powders and SRF powder
- This approach provides capability of tailoring ignition temperature, burn duration, and ignition delay of the ignition process for different applications

Photo-ignition of CNT for Space Applications

- CNT ignition offers certain benefits for space and DoD applications:

  - Light weigh, low cost , and compact, currently < 50 g & 5x2x1 cm^3

  - Extreme miniaturization is possible by flash LEDs in the near future i.e. ignition capsule with built in LED source

  - Very safe, multi-level safeguard against external interference

  - Very reliable, based on proven Xe-flash technology & LEDs

  - Scalable with potential applications in small and large rockets

  - Space qualifications is expected with no major issues

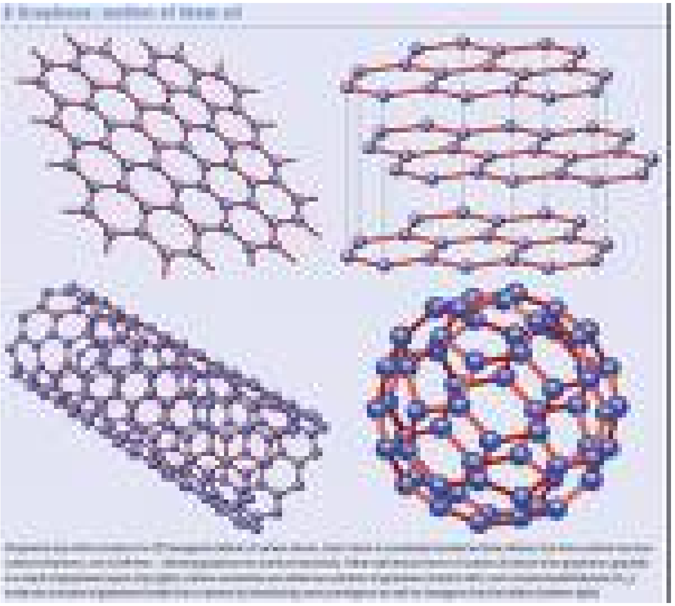
- The ignition capsule can be used as an ultra-light weight rocket (or as an integral part of it) for maneuvering small space vehicles
- Ignition of polymer laminated CNTs with a solid oxidizer (such as AP) indicates that photo-ignition can be achieved where environmental oxygen is not available (work in progress)

Backup Slides

Graphene Oxide (GO),
Alternative Nano-material for Photo-ignition

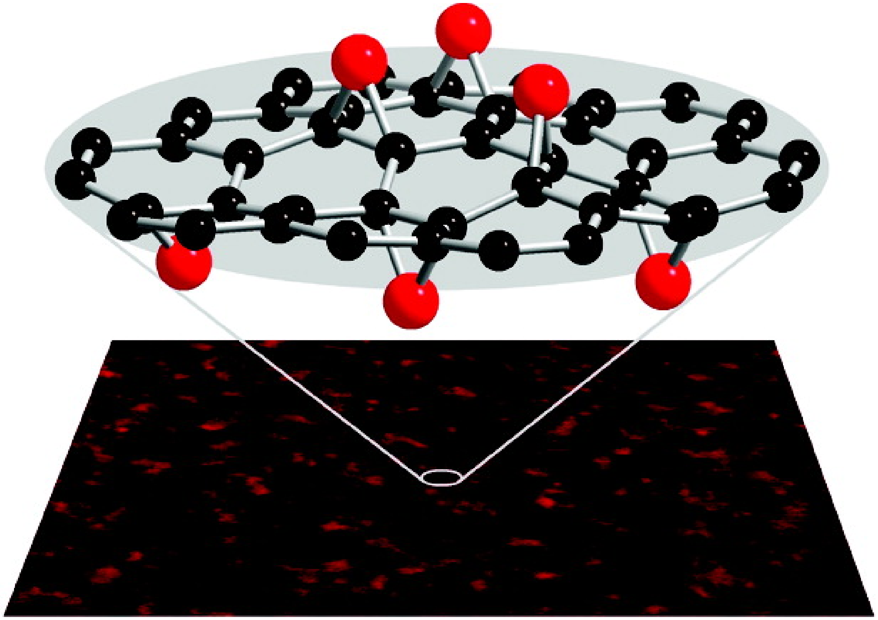
Structure of Graphene:

- **Graphene** is a 2D honey-comb lattice of carbon atoms. **CNTs** and **fullerenes** are rolled up structures made of graphene sheets



Graphene Oxide (GO):

- GO is made of graphene layers with out-of-plane oxygen atoms attached to carbon. GO may have a wide range of O/C ratio.



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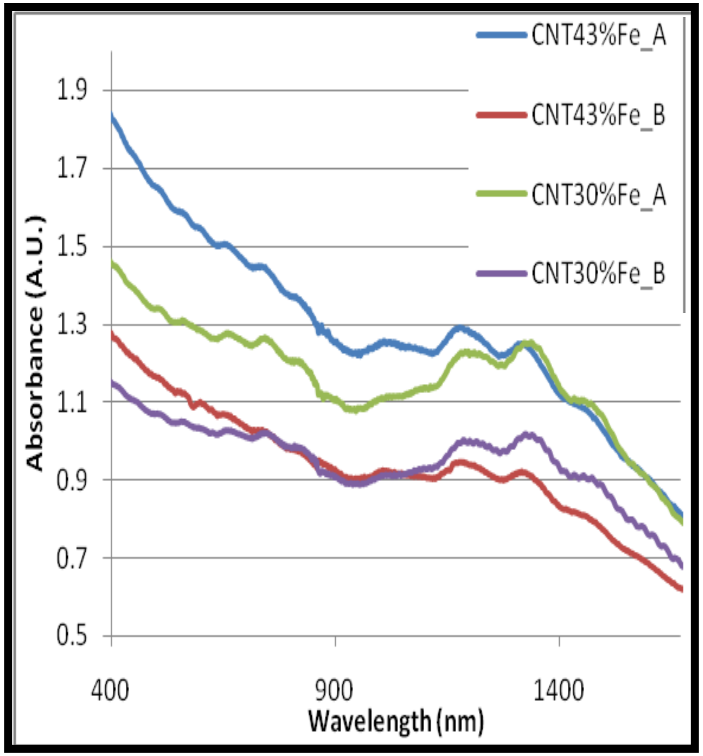
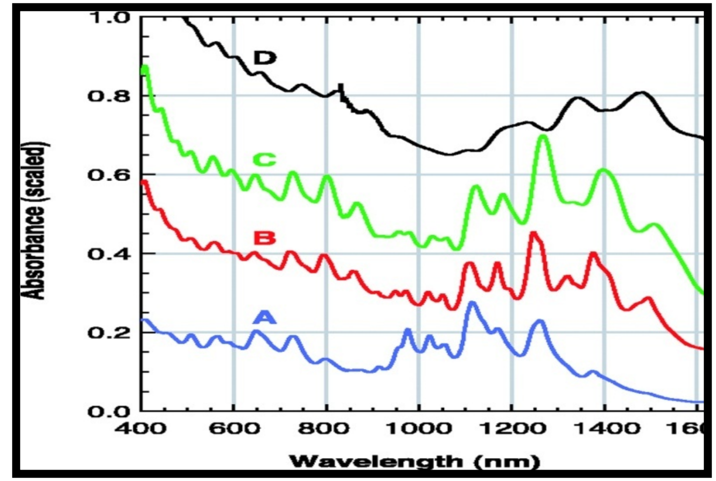
Absorption Spectra of SWCNT





Absorption spectra of fullerene nanotubes in SDS-D2O suspension. The top trace D is typical of tubes prepared in suspension without centrifugation. The broadened and red-shifted absorption features show that most nanotubes in the sample are aggregated in small bundles. Trace C is from individual SDS micelle coated nanotubes after addition of PVP. Traces B and A are from samples of individual nanotubes separated and solubilized by SDS micelles. Nanotubes in sample A have a smaller average diameter than in B because they were grown under a higher CO pressure.

- Absorption of SWCNTs samples measured by VIS-NIR spectrometer.
- These curves and the optical transitions between 950-1460 nm are in agreement with the absorption of SWCNTs that is reported in the literature.
- Our SWCNTs is a broadband absorber with weak wavelength (λ) dependency, which explains the finding that minimum ignition energy is independent of λ

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